Organic Permeable Base Transistors
"Schottky-type Contacts in Ultra-Short Channel Organic Semiconductor Devices for GHz-Operation“

Dr. Hans Kleemann, Group Leader // October, 1st, 2020
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Organic Thin-Film Transistors (OTFTs) are the technology of choice for flexible electronic devices (active matrix displays, wireless communication, smart tags, etc.)

BUT: Requirements for e.g., high resolution display driving are very demanding and cannot be fulfilled by today's OTFT technology

- Column drivers need to operate at 5...10MHz for 200ppi displays [1]
- Select transistor should turn on in less than 10ns (or transition frequency of >50MHz)

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  • Column drivers need to operate above 10MHz for 200ppi displays [1]
    → fastest OTFT oscillator at 6.3MHz [2]

  • Select transistor should turn on in less than 10ns (or transition frequency of >50MHz)
    → fastest OTFT operates at 38MHz [3]

[1] Kubota et al., 10.1109/TED.2011.2175395
[2] Borchert et al., 10.1126/sciadv.aaz5156
Vertical Organic Transistors

- **Vertical Transistors (inspired by the triode approach)**
  - Ultra-short channel (<300 nm) and high gate control
  - Potential for reduced overlap capacitance
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Organic Permeable-Base Transistors (OPBT)

- Base film is a 15nm thick aluminum film surrounded native $\text{Al}_2\text{O}_3$
- Strain-induced pin-hole formation during oxidation → 2...5nm pin-holes
- $\text{AlO}_x$ quality can be improved by wet-chemical anodization, allows for thicker base layers, too. [5]

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- Excellent transistor performance, on/off $10^8$, 60..90 meV/dec, transmission >99.9998%
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Organic Permeable-Base Transistors (OPBT)

- Using dynamic (time-resolved) measurements record transition frequency of 40MHz was obtained
- Even up to 100MHz possible (tool with higher output power required)

\[ f_{\text{t}} \]

Schottky-Contacts in OPBTs

- **OPBTs have at least 3 Schottky-Contacts**
  - Injection electrode at the Emitter – Metal-C60 contact
  - Base-Electrode – Al-C60 contact
  - Ejection electrode at the collector – metal-C60 contact.
- **Schottky-Contact at Emitter and Collector are not desired** → possible source of contact limitation
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  - **Schottky-Contact at Emitter** electrode can be **eliminated by n-type doping**
    → e.g., W2(hpp)4 conductivity up to 10S/cm and chemical potential as close as 70meV to the LUMO
  - However, n-type doping is difficult to use for the Schottky-contact at the collector (due to air exposure for base oxidaton)
  - Usually, Al would be a preferred electrode material due to matching work function, but Al forms AlOx at the interface
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    → e.g., W2(hpp)4 conductivity up to 10S/cm and chemical potential as close as 70meV to the LUMO
  - **Cr/Al electrodes** are used instead of pure Al
    → oxidation of Al seen at the base electrode, **Cr does not oxidize easily**
    → Ohmic contact.
Schottky-Contacts in OPBTs

- In OPBTs, the current is limited by a space-charge-limited current and not by the resistance of the Schottky-Contacts nor the density of pinholes
- OPBTs are purely limited by the conductivity of the organic semiconductor and not the density or distribution of pinholes [8]

Schottky-Contacts in OPBTs

- Schottky-Contact at the base is the key for the high performance of OPBTs
  - In depletion, organic semiconductor is fully depleted → good off-state

\[ E_F \]

\[ \text{metal} \quad \text{insulator} \quad \text{n-type} \]

Depletion

![Graph showing capacitance vs. voltage for different i-C\textsubscript{60} thicknesses](image)

- Capacitance (nF/cm\textsuperscript{2})
- Voltage [V]
- i-C\textsubscript{60} thicknesses: 50 nm, 100 nm, 200 nm, 400 nm
Schottky-Contacts in OPBTs

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  - In depletion, organic semiconductor is fully depleted → good off-state
  - Very high capacitance in accumulation (~2µF/cm²) → high on-current density
  - Native Oxide + annealing → high-quality MOS interface with low defect density and good current blocking

![Diagram of Schottky Contacts]

![Graph of Capacitance vs Voltage]

\(E_F\)  
metal  
insulator  
n-type  
Al  
AlO\(_x\)  
C\(_60\)
Stability of OPBTs

- Quality of Schottky-Contact is important for device stability
- OPBTs only show significant bias-stress at elevated temperature (reversible) – but stress is not field, current or illumination driven

Double-Base OPBTs

- Even multiple base electrodes can be incorporated
- Each base has full control over the transistor function → can shift on- and off
- Turn-on voltage of Base1 can be tuned by Base2

![Diagram of Double-Base OPBTs](image)
Double-Base OPBTs

- Double-Base OPBTs used for logic gates (NAND, AND, NOT)
- Operation at <4V
- Operation at frequency >10MHz
- Fall and rise time <50ns
- Gain of unipolar circuit ~10

Double-Base OPBTs

- Double-Base OPBTs used for logic gates (NAND, AND, NOT)
- Connected with p-type OPBT
- Operation at <4V
- Operation at frequency >50MHz
- Fall and rise time <10ns
- Gain of complementary circuit ~25

Summary

- OPBTs are ultimate short-channel OTFTs and their function relies on 3 impact Schottky-Contact
- Ohmic Injection can be ensured using doping and proper choice of metals
- Al/C60 Schottky-Contact at the base is most important transistor operation
  - High accumulation capacitance $\rightarrow$ high on-current
  - Low depletion capacitance $\rightarrow$ high on/off
  - Low Defect density $\rightarrow$ excellent device stability

Even multiple base electrodes might be incorporated into OPBTs
$\rightarrow$ logic gates with high gain and high operation frequency fabricated
Thank you!

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